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Effects of disparity–perspective cue conflict on depth contrast

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Abstract

The role of disparity–perspective cue conflict in depth contrast was examined. A central square and a surrounding frame were observed in a stereoscope. Five conditions were compared: (1) only disparity was introduced into either the centre or surround stimulus, (2) only perspective was introduced into the centre or surround, (3) concordant perspective and disparity were introduced into the centre or surround, (4) disparity was introduced into one stimulus and perspective into the other, and (5) only the centre stimulus was presented with horizontal shear disparity and perspective manipulated independently. The results show that individual differences in depth contrast were related to individual differences in the weighting of disparity and perspective in the single-stimulus conditions. We conclude that conflict between disparity and perspective contributes to depth contrast. However, significant depth contrast occurred when there was no disparity–perspective cue conflict, indicating that this cue conflict is not the sole mechanism producing depth contrast.

Keywords: Depth contrast; Binocular disparity; Stereopsis; Perspective

1. Introduction

Apparent depth of a visual stimulus is affected by not only the binocular disparity in the stimulus itself but also by disparity in an adjacent stimulus. For example, when a stimulus in a frontal plane is surrounded by an inclined stimulus, it appears inclined in the opposite direction to the surround. This illusory inclination induced in the centre is called depth contrast (Werner, 1937, 1938; Pastore, 1964; Pastore & Terwilliger, 1966; Graham & Rogers, 1982; Kumar & Glaser, 1991, 1992, 1993; van Ee & Erkelens, 1996b; van Ee, Banks, & Backus, 1999).

Some authors have suggested that depth contrast is due to low sensitivity of the human visual system to the absolute angle of disparity-induced inclination and high sensitivity to the relative angle between objects (Howard & Rogers, 1995; van Ee & Erkelens, 1996b). Howard and Rogers (1995) proposed a normalization theory of depth contrast, which can be summarized by the following propositions concerning the ways in which two planar surfaces interact in the perception of inclination:

1. In general, single surfaces seen in isolation tend to normalize to the frontal plane (Gillam et al., 1984, 1988; van Ee & Erkelens, 1996a; Pierce & Howard, 1997). However, the relative slope of two adjacent surfaces is well perceived because a second-order disparity gradient provides primary information for the visual system to estimate relative depth.
2. The mean perceived slope of a pair of adjacent surfaces tends to normalize to the frontal plane while the relative slope is perceptually preserved. For example, when a frontal surface is placed adjacent to an inclined surface, they normalize as a pair. As a result, the sloping surface appears more inclined than when in isolation and the frontal surface appears inclined in the opposite direction to that of the sloping surface. The first effect is depth enhancement (Pierce & Howard, 1997) and the second is depth contrast.
3. For two surfaces with a given relative slope, anything which reduces the perceived slope of one surface increases the perceived slope of the other. For example, the induced slope in a frontal surface will increase to the extent that the perceived slope of the inducing surface decreases.

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4. It follows from proposition 2 that anything which reduces the perceived relative slope between two surfaces reduces both depth enhancement and depth contrast. For example, separating two surfaces laterally or in depth has this effect (Gillam & Blackburn, 1998).

Howard and Rogers stated that normalization causes surfaces to appear less inclined than they are. In normalization, a stimulus which is to one side of a norm in a sensory dimension, appears more similar to the norm than it is. Thus, a tilted line appears more vertical than it is, a moving object appears to slow down. In depth normalization, one can say that depth ramps normalize to the norm of zero-disparity gradient.

However, underestimation of the slope of a surface could also be due to conflict between depth cues. For example, in a random-dot stereogram with horizontal shear disparity (a first-order disparity gradient along a vertical axis), binocular disparity is geometrically predicted to produce inclination about a horizontal axis. However, the zero texture gradient indicates that the surface is in a frontal plane. It is known that perspective is used as a depth cue although it does not provide unambiguous information (Gillam, 1968; Youngs, 1976; van der Meer, 1979; Buckley & Frisby, 1993; Cumming, Johnston, & Parker, 1993; Allison & Howard, 2000). It has also been shown that some observers use binocular disparity while others use perspective for depth estimates when the two cues conflict (Gillam, 1968; Allison & Howard, 2000).

This study was designed to reveal the role of disparity–perspective cue conflict in depth contrast. A surface will appear more inclined when disparity and perspective are concordant than when the two cues are in conflict. If the relative angle between two surfaces is preserved, it is predicted that depth contrast will be reduced when the inducing surface appears more inclined. It is also predicted that individual differences in depth contrast are related to individual differences in the weights assigned to perspective and disparity. For example, we predict that a subject who relies on perspective in a conflict situation will perceive more depth contrast when only disparity is introduced.

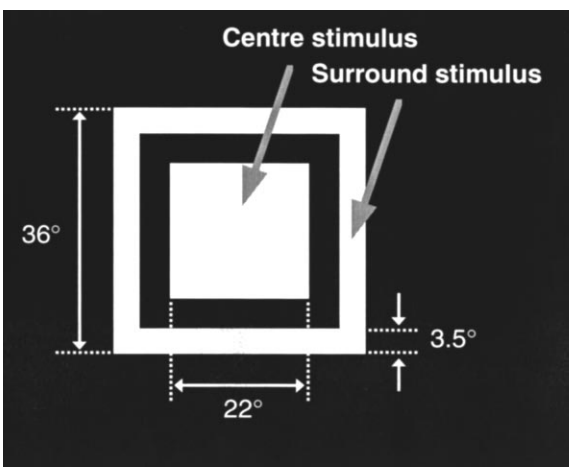

Fig. 1. Stimulus configuration for the two-surface condition. In the single-surface condition, only centre stimulus was presented.

2. Experiment 1: matching

2.1. Visual display

The stimulus was generated by a Macintosh Quadra 700 computer and rear projected on a screen by an Electrohome projector. Subjects observed the stimulus through liquid crystal shutters at a frame rate of 75 Hz (37.5 frames/s to each eye) at a viewing distance of 113 cm.

Fig. 1 shows the stimulus configuration. Horizontal shear disparity and/or linear perspective were introduced into the central square or the surrounding frame. A textured pattern would provide richer perspective and disparity information distributed. However, considering the limitation of spatial resolution of the display, we used the simplest pattern to examine the influence of disparity and perspective. An anti-aliasing technique was used to reduce the pixelation problem. The anti-aliased pattern was a black-white pattern, but in a region where a pixel straddled the boundary, the pixel was painted with 128-level grey scaled to the ratio of an imaginary white area in the pixel to the whole pixel area. Each pixel was a square with side 5.5 arcmin at the centre of the screen. The luminance of the stimulus was 1.1 cd/m^2, which was chosen so that crosstalk between the eyes was not visible. The background of the stimulus and the experimental room were carefully darkened so that nothing but the stimulus was visible.

Four two-surface conditions and one single-surface condition, in which only the centre stimulus was presented, were compared.

2.1.1. Disparity-only condition

Horizontal shear disparity was introduced either into the centre or into the surround stimulus. This is typical of stimuli used in most previous studies on depth contrast, in which only horizontal disparity was introduced into the stimulus. Disparity was chosen so that the geometrically-predicted inclination about a horizontal axis was -30, -15, 15, or 30° (a positive value indicates top away). For instance, horizontal shear disparities were $\pm 0.88°$ or $\pm 1.9°$ (right and left eye images were sheared 0.44° or 0.95° in the opposite direction) when the interocular distance of a subject was 65 mm. Correct disparity values were calculated for each observer according to the interocular distance, which varied from 58 to 68 mm.

2.1.2. Perspective-only condition

Linear perspective was introduced into the centre or into the surround. This condition is similar to viewing a two-dimensional picture binocularly. Linear perspective transformed the stimulus into a trapezoid. Perspective distortion was calculated to simulate a flat square surface inclined about a horizontal axis at -30, -15, 15, or 30° at the viewing distance. This stimulus was designed to reveal whether perspective alone induces illusory inclination in an adjacent region.

2.1.3. Concordance condition

Concordant disparity and perspective were introduced into the centre or into the surround. This condition is closer to viewing a natural three-dimensional scene than the others although accommodation and other cues are in conflict. Comparison of this condition with the disparity-only condition is the main interest in this paper.

2.1.4. Mixed-conflict condition

Disparity was introduced into the centre and perspective into the surround, or perspective was introduced into the centre and disparity into the surround. The directions of both cues were chosen to support the contrast effect cooperatively. For instance, disparity specifying $-30°$ inclination was introduced into the surround and perspective specifying $+30°$ inclination was introduced into the centre. Thus, both cues specified the same inclination but with reversed sign. We predicted that this artificial condition would produce large illusory inclination.

2.1.5. Single-surface condition

Only the central stimulus was displayed. Disparity and perspective had values appropriate for geometric ally-predicted inclinations of -30, -15, 0, 15, or 30°. Twenty-five combinations were tested.

2.2. Response measures

A circular paddle, 18 cm in diameter, was placed in front of the subject at waist height. The paddle could be rotated about a horizontal axis. The subject could not see the paddle. The subject was asked to rotate the paddle until it felt inclined to the same angle as the visually perceived inclination.

In a control condition, the screen was replaced by a real board. The subject set the unseen paddle to match the inclination of the board. The board was the same size as the centre stimulus in the main experiment. It was covered with a grid pattern and had a full range of binocular and monocular depth cues. A rod and a frame supporting the board were also visible to the subject. The board was inclined at ± 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, or 80°, making 23 values in all. The subject made four settings for each inclination.

The functions relating the paddle response to the real surface inclination were monotonic but non-linear. For most subjects, the inclination of paddle was less than that of the board and this underestimation was more severe for top-near than for top-far inclination. In previous studies in our laboratory (e.g. Howard & Kaneko (1994)), a third-order polynomial function was used to fit the calibration data for each subject. However, fitting with a third-order function to the present data showed a slight but systematic error. To remove this residual error, we used a fifth-order polynomial function in the present study. The fifth-order functions were used to calibrate the manual settings in the main experiment.

2.3. Procedure

The subject observed the stimulus for 10 s with the chin supported on a chin rest. A beep signal was given as a cue for paddle setting. In a trial where both the centre and surround stimuli were presented, the subject matched the paddle to the centre and surround successively. The stimulus remained until the paddle settings were completed.

Kumar and Glaser (1993) reported that depth contrast decreased when the stimulus duration increased. However, when we tried to use a short duration in the present experiment, the observers had difficulty in setting the paddle. A pilot study showed substantial contrast occurred with long duration. We used a long duration to ensure that the observer would make a stable response.

In each session, 57 trials were executed in random order. Of these, 32 were two-surface conditions (4 (depth cue combination) $\times$ 4 (disparity and/or perspective magnitudes) $\times$ 2 (centre had depth cues or surround had depth cues)) and 25 were single-surface conditions (5 (disparity magnitudes) $\times$ 5 (perspective magnitudes)). Five repeat sessions were carried out for each subject.

2.4. Subjects

Four males and two females with normal stereopsis participated in the experiment. Their ages ranged from 26 to 37.

2.5. Results and discussion

Fig. 2 shows perceived inclinations in the single-surface conditions. The abscissa shows the geometrically-predicted inclination due to horizontal shear disparity. Positive values indicate top away. The separate curves are for different predicted inclinations due to perspective, as indicated in the legend. Error bars indicate ± 1 standard error of the mean. If a subject used binocular

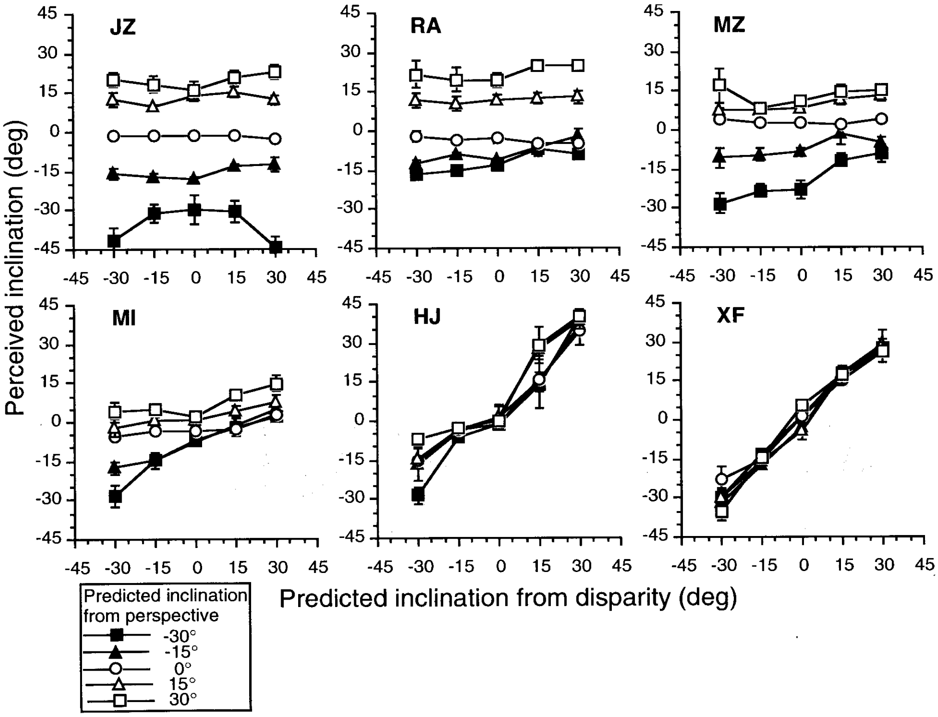

Fig. 2. Perceived inclination in the single-surface conditions.

disparity exclusively for depth information, the data would be on a straight line with slope 1. If a subject used perspective and ignored disparity, data would be on a line with slope 0. Subjects XF and HJ used binocular disparity exclusively or almost exclusively. For these subjects, changes in linear perspective had little or no effect on perceived inclination. For subjects JZ, RA, and MZ, perceived inclination depended strongly on perspective. Subject MI was affected by both cues.

Fig. 3 shows perceived inclinations in the two-surface conditions for subject JZ. Fig. 3A shows the results of the disparity-only condition. Disparity was introduced into the surround. The centre had no disparity. Strictly speaking, horizontal disparity would occur in the centre when it was not centrally fixated. However, ‘no disparity’ or ‘zero disparity’ indicates that a horizontal shear disparity was not introduced into a specified stimulus. The abscissa shows the predicted inclination specified by the disparity in the surround. The ordinate shows perceived inclination. If the perceived inclination is verldical, (determined by disparity in the stimulus), the data points for the surround (■) would be on a straight line with slope 1 and those for the centre (□) would be at 0. Perceived inclination deviated substantially from the geometrical prediction. The disparate surround (■) appeared less inclined than prediction and the zero-disparity centre (□) appeared inclined in the opposite direction to the surround (depth contrast). Fig. 3B shows the results of the perspective-only condition. Perspective was introduced into the surround so that the surrounding frame was a trapezoid and the centre stimulus was a square. The surround appeared inclined according to perspective although inclination was underestimated when perspective inclination was $\pm 30°$. Induced inclination was not perceived in the central square. Fig. 3C shows the results of the concordance condition, in which concordant disparity and perspective were introduced into the surround stimulus. The surround appeared inclined according to the concordant depth cues although it deviated slightly from the true value. The centre appeared inclined in the opposite direction to the surround (depth contrast). Fig. 3D shows the results of the mixed-conflict condition, in which the surround had disparity and the centre had perspective. The abscissa shows the predicted inclination specified by the disparity in the surround. Inclination specified by perspective in the centre was equal and opposite to that specified by disparity in the surround. Thus, disparity specified inclination corresponds to a straight line with slope 1 for the surround (■) and slope 0 for the centre (□). Perspective specified inclination corresponds to a straight line with slope 0 for the surround (■) and slope -1 for the centre (□). The results seem to indicate that the observer used only perspective information and completely neglected the disparity information. However, perceived inclination was also influenced by disparity because when only perspective was introduced into the stimulus, perceived inclination was much smaller than when a disparity was introduced into the surround. This will be shown in Fig. 4B′.

We fitted regression lines to the functions shown in Fig. 3 to quantify perceived inclination. The slopes of the regression lines were taken as a measure of the contrast effect. Fig. 4 shows the slopes of the regression lines fitted to the results of six observers.

Fig. 4A and A′ show the results of the disparity-only conditions. In Fig. 4A the surround had disparity. Inclination of the disparate surround was underestimated relative to veridical perception corresponding to 1. Underestimation was particularly obvious for observers JZ, RA, MZ, and MI. Grey bars show the perceived inclination of the zero-disparity centre. Negative values indicate that the stimulus appeared inclined in the opposite direction to the disparate surround (depth contrast). Induced slope was relatively large for JZ, HJ, and XF and small for MZ. In Fig. 4A′ the centre had disparity. In this condition, the disparate stimulus appeared more inclined and the zero-disparity stimulus less inclined than when the surround had disparity. The combined change of perceived inclination of the centre and surround stimuli so as to preserve the relative inclination is consistent with the propositions introduced in the Introduction. However, the normalization theory states that depth underestimation is caused by normalization to the frontal plane. This can not explain this centre-surround asymmetry. Why depth is underestimated more and illusory depth is induced more when a surround has a disparity than when a central object has a disparity is a question.

Fig. 4B and B′ show the results of the perspective-only conditions. In Fig. 4B the surround was tapered and in Fig. 4B′ the centre was tapered. In both cases, the tapered stimulus appeared inclined in the direction with the shape transformation being interpreted as perspective. Induced inclination in the other stimulus (indicated by grey bars) was very small or zero, even though the surrounding or adjacent stimulus appeared inclined. This indicates that binocular disparity plays an important role in depth contrast.

Fig. 4C and C′ show the results of the concordance conditions. In Fig. 4C the surround had concordant disparity and perspective and in Fig. 4C′ the centre had concordant disparity and perspective. In these conditions, the perceived inclination of the disparate stimulus

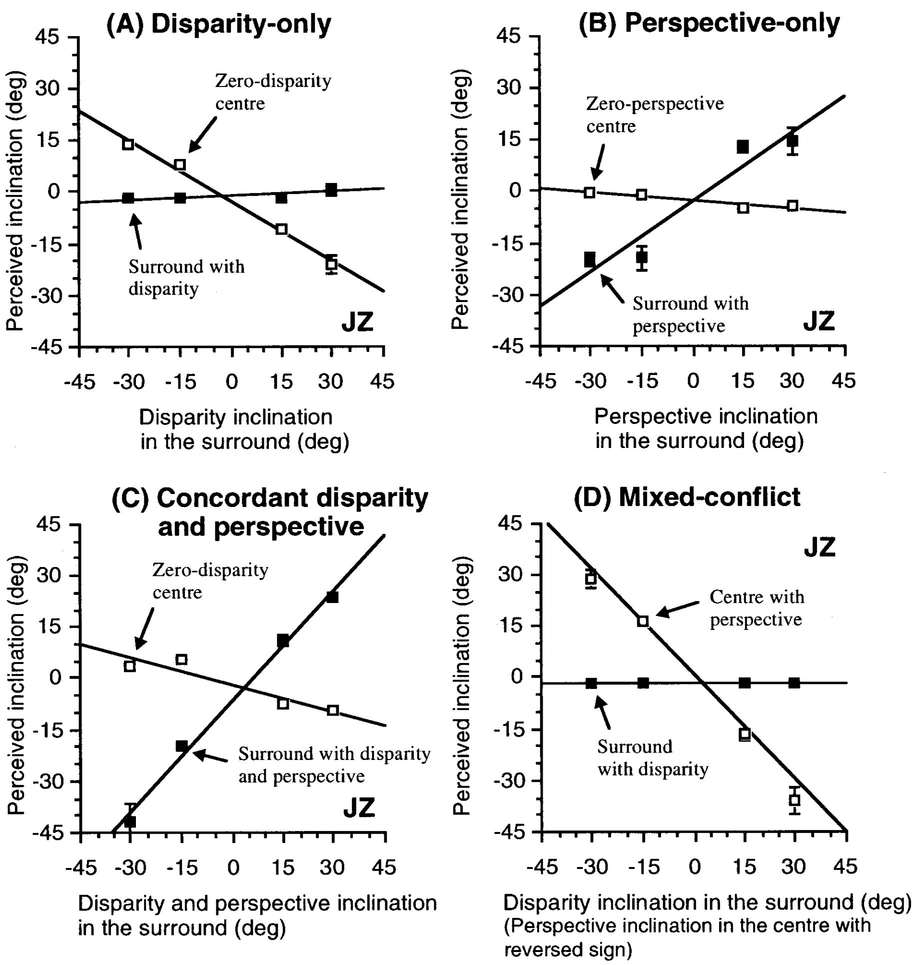

Fig. 3. Perceived inclination in the two-surface conditions for one observer JZ.

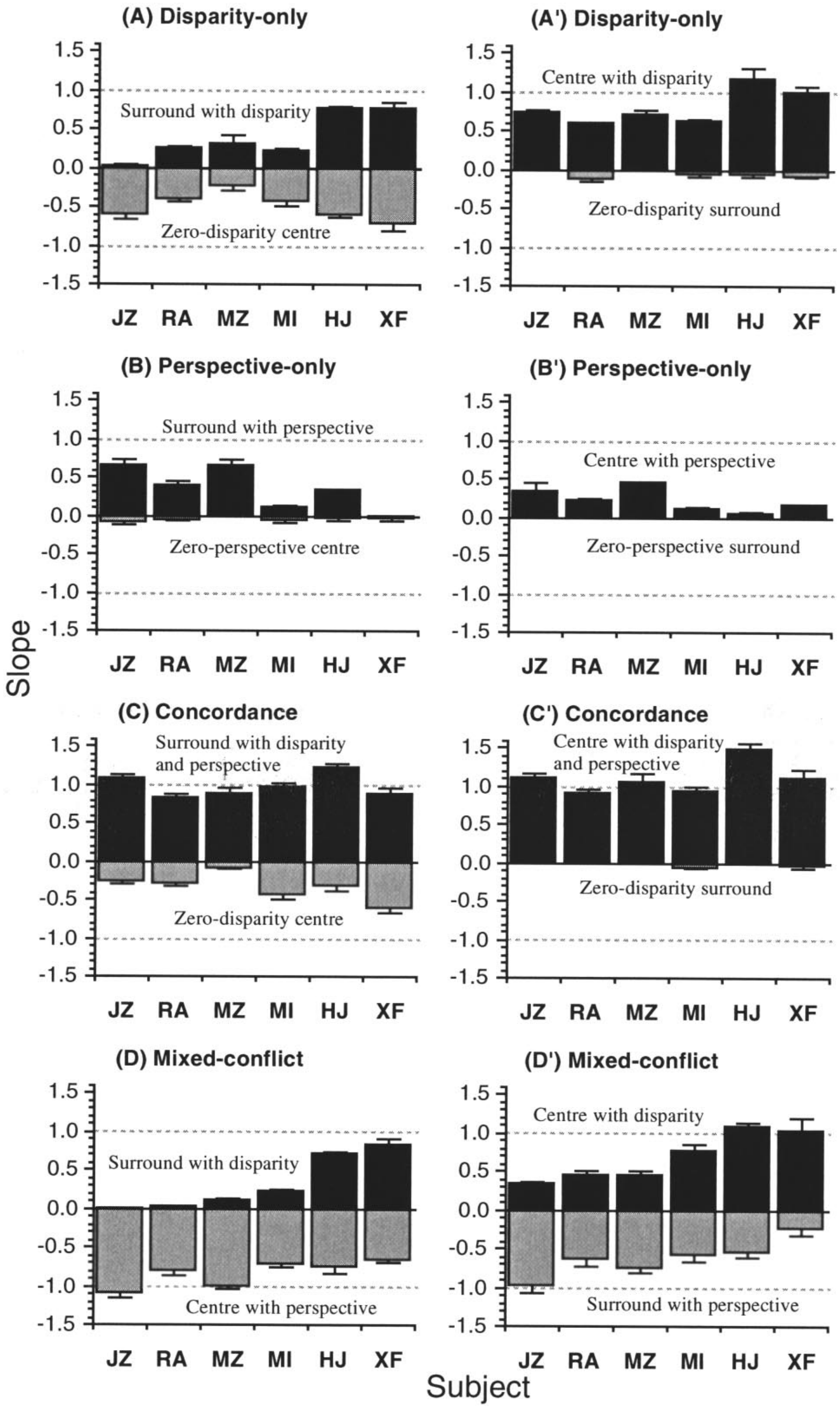

Fig. 4. Perceived inclination in the two-surface conditions for six observers.

was much larger than in the disparity-only condition. Substantial induced slope was observed in the centre when the surround had disparity.

Fig. 4D and D′ show the results of the mixed-conflict conditions. In Fig. 4D the surround had disparity and the centre had perspective. In Fig. 4D′ the centre had disparity and the surround had perspective. That is, inclination specified by disparity corresponds to 1 for the stimulus with disparity (indicated by black bars) and to 0 for the stimulus with perspective (indicated by grey bars). Inclination specified by perspective corresponds to 0 for the black bars and to -1 for the grey bars.

Fig. 5 shows the effects of a zero-disparity surround on perceived inclination of the centre stimulus. Black bars show perceived inclination of the centre in the two-surface conditions. These data were re-plotted from Fig. 4. Hatched bars show perceived inclination of the same stimulus when presented singly. These data were calculated from the results of the single-surface conditions shown in Fig. 2.

As shown in Fig. 5A in the disparity-only condition, for JZ, RA, MZ, and MI, the isolated square produced a very weak impression of depth in spite of the disparity (hatched bars). However, when a zero-disparity surround was presented at the same time, inclination of the same stimulus increased (black bars). This effect of a zero disparity stimulus is consistent with previous studies (Gillam et al., 1984, 1988; van Ee & Erkelens, 1996a). Pierce and Howard (1997) referred to this effect as depth enhancement. As shown in Fig. 5B when a stimulus with perspective was presented singly, RA, JZ, and MZ perceived substantial inclination in the stimulus (hatched bars). However, when the surround was presented at the same time, perceived inclination decreased (black bars).

This indicates that binocular disparity becomes dominant even for the perspective-dependent subjects when two different inclinations are seen at the same time. These observers require binocular disparity to perceive different inclinations at the same time but perspective is the dominant cue for judging the absolute inclination. For instance, in Fig. 4B′, C′ and D, perspective-specified inclinations were the same. The centre stimulus was tapered and the surround stimulus was a square. In Fig. 4C′ the centre stimulus appeared inclined according to concordant disparity and perspective. In Fig. 4D, disparity was transferred from the centre to the surround. However, JZ, RA, and MZ perceived large inclination in the centre with the direction and amount specified by perspective. Which stimulus had disparity was not important for them. However, this does not mean that the disparity had no effect for these observers because, when the disparity was removed, perceived inclination of the centre decreased much as shown in Fig. 4B′.

3. Experiment 2: cancellation

In many previous studies on depth contrast a cancellation method was used to quantify the magnitude of induced depth. In the cancellation method the disparity required to make the test stimulus appear in a frontal plane is taken as a measure of depth contrast. Although

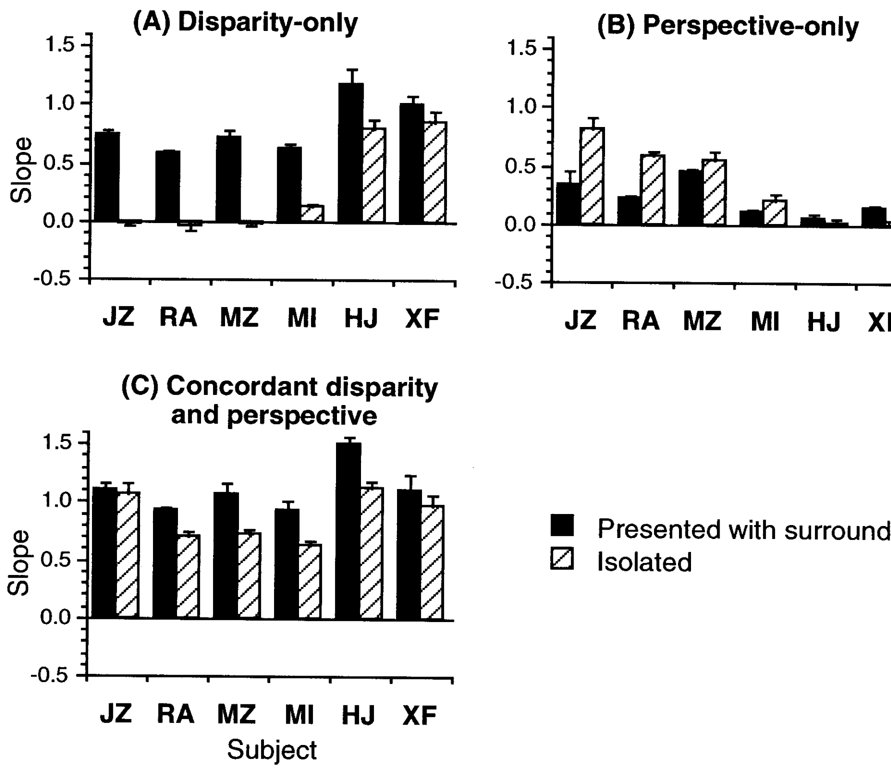

Fig. 5. Effects of zero-disparity surround on perceived inclination of the centre stimulus.

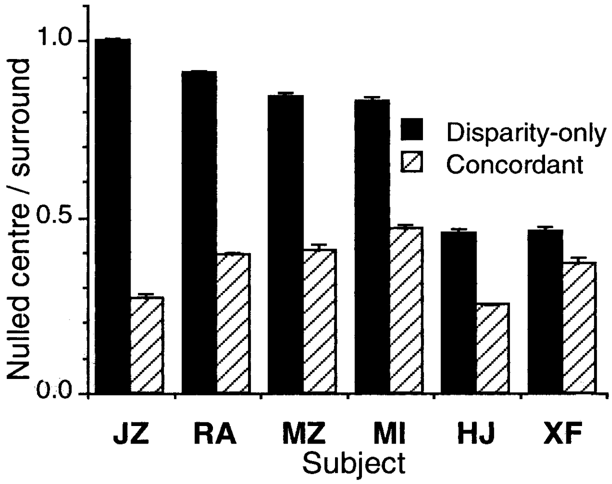

Fig. 6. Depth contrast measured with the nulling method. Required disparity inclination in the centre stimulus to make it appear in the frontal plane as a fraction of the disparity inclination in the surround stimulus.

this is a sensitive method it involves a change in the stimulus and may therefore not reveal the amount of induced depth in the original stimulus. The matching method used in experiment I avoids this problem. In experiment 2, we used the cancellation method using the same stimulus configuration and the same observers to compare the two methods.

3.1. Visual display

The stimulus consisted of the centre and the surround stimuli with the same sizes and shapes as in experiment 1. Two conditions were compared.

3.1.1. Disparity-only condition

The surround had a horizontal shear disparity to produce geometrically predicted inclinations of −30, −15, 15, or 30°. The subject adjusted the disparity in the central stimulus so that it appeared in a frontal plane.

3.1.2. Concordance condition

The surround had concordant horizontal shear disparity and perspective. The sizes of both cues were chosen to produce geometrically predicted inclinations of −30, −15, 15, or 30°. The subject adjusted both the horizontal shear disparity and perspective in the centre stimulus so that it appeared in a frontal plane.

3.2. Procedure

The subject adjusted the horizontal shear disparity (and perspective in the concordance condition) in the centre stimulus with two keys on a computer keyboard. Each time a key was pressed, disparity (and perspective) in the centre stimulus increased or decreased to produce a 1° step in inclination.

Thirty two trials (2 (only-disparity or concordance conditions) $\times$ 4 (inclination values of surround) $\times$ 4 (repetition)) were executed in random order in one session. Two repeat sessions were carried out for each subject.

3.3. Subjects

The same six subjects used in experiment 1 participated in this experiment.

3.4. Results

Fig. 6 shows the horizontal shear disparity required to make the centre stimulus appear in a frontal plane. It is indicated as a fraction of the disparity in the surround. For example, 0.5 indicates that when the disparity inclination in the surround was 30° a disparity predicted to produce 15° inclination was introduced into the centre.

The perspective-dependent subjects JZ, RA, MZ, and MI showed very large depth contrast in the disparity-only condition. For these observers, depth contrast was much reduced when the inducer had concordant disparity and perspective. The disparity-dependent subjects HJ and XF showed less contrast in the disparity-only condition than the other subjects. In the concordance condition, less but significant contrast was found for every observer. In this condition, individual difference was not obvious.

4. General discussion

The present results show that some observers rely more on binocular disparity and others more on perspective for depth estimates when the two cues are in conflict. This is consistent with previous research (Gillam, 1968; Allison & Howard, 2000). Based on the results of the single-surface conditions shown in Fig. 2, observers JZ, RA, MZ, and MI can be classified as perspective-dependent and observers HJ and XF as disparity-dependent.

In experiment 1 perceived inclination was measured with a matching method. The disparity-only condition with the disparate surround is comparable to the conditions used in most previous studies on depth contrast, in which only disparity was introduced into the surrounding or flanking stimulus and perspective was in conflict. As shown in Fig. 4A, observers JZ, RA, MZ, and MI perceived much less inclination in the disparate surround (indicated by black bars) than predicted from the disparity (indicated by a dotted line) while disparity-dependent subjects HJ and XF perceived more inclination than other subjects. This is consistent with the results of the single-surface conditions. The zero-disparity centre appeared inclined in the opposite direction to the inducing stimulus for every observer (indicated by grey bars). This was prominent for JZ, HJ, and XF.

This contradicts our initial predictions that the angle between the surfaces would be preserved for every observer and that observers who underestimated the inducing depth would show large induced depth. We based these predictions on the results of a previous study, in which a random-dot stimulus was used (Sato & Howard, 1997). Five of the six observers (JZ, RA, MI, HJ, and XF) participated in the previous experiment. The comparison between the previous results and the present results are shown in Fig. 7. The random-dot stimulus used in the previous study consisted of a zero-disparity central disc with 8.0° diameter and a disparate annular surround with 8.0° inner diameter and 31.2° outer diameter. The results for solid-square stimulus were replotted from Fig. 4A.

The difference of perceived inclinations between these two conditions can be explained if assumed that the solid-square stimulus provided stronger perspective information than the disc-shaped random-dot stimulus. In both conditions, disparity specified that the surround was inclined and that the centre was frontal. Perspective specified that both centre and surround were frontal. In the random-dot stimulus, subjects HJ and XF perceived larger inclination in the disparate surround (white bars) and smaller inclination in the zero-disparity centre (hatched bars) than the other three subjects. Perceived inclinations for HJ and XF were relatively close to the disparity-specified inclinations because they relied on disparity. Perspective-dependent subjects underestimated inclination in the disparate surround because perspective specified that the surface was frontal. However, the angle between the surfaces specified by disparity was not ignored presumably because a second-order disparities provided strong depth information. As a result, an illusory inclination was induced in the zero-disparity centre. In the solid-square stimulus, disparity-specified and perspective-specified inclinations were the same as in the random-dot stimulus. However, HJ and XF underestimated the inducing inclination and perceived larger illusory inclination than in the random-dot stimulus. We suggest that this is because the solid-square stimulus provided stronger perspective information than the random-dot stimulus. HJ and XF could not ignore the strong perspective information specifying zero inclination and underestimated the inducing slope. Illusory depth was perceived in the same way explained above. For RA and MI, the inducing surface was underestimated and relative inclination was also underestimated, presumably because perspective information was strong enough to overcome the relative-angle constraint. For JZ, perceived inclinations were different from those for the other two perspective-dependent observers. The change of perceived inclinations caused by the stimulus patterns was similar to that for HJ and XF although the relative inclinations were smaller than those for HJ and XF.

We conclude that perspective specifying zero inclination has two distinct effects on depth contrast. Zero perspective in the inducing surface causes its inclination to be underestimated. This produces illusory inclination in the zero disparity surface with a given relative inclination specified by disparity. Zero perspective also reduces induced inclination if the perspective information is strong enough to reduce the effects of relative inclination.

In experiment 2 a cancellation method was used to quantify depth contrast and the results seem to be

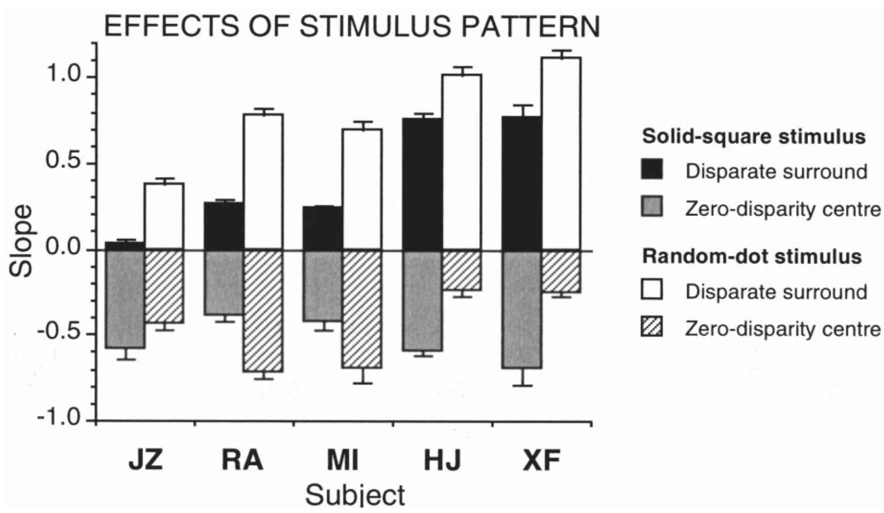

Fig. 7. Comparison between the solid-square stimulus in the present study and the random-dot stimulus in the previous study (Sato & Howard, 1997).

closer to our original prediction than those of experiment 1. Thus, perspective-dependent subjects perceived large depth contrast in the disparity-only condition and depth contrast was reduced in the concordance condition. In the disparity-only condition of experiment 1, induced depth for the perspective-dependent subjects was not larger than that for the disparity-dependent subjects. Why did the perspective-dependent observers show very large depth contrast when the cancellation method was used? We explain the difference in the following way. In the disparity-only condition, perspective-specified inclinations were zero for both the centre and surround stimuli. The results of the single-surface conditions of experiment 1 (Fig. 2) show that, when presented singly, each stimulus appeared frontal for the perspective-dependent subjects in spite of disparity. However, when two surfaces with different disparity were presented at the same time, relative inclination was perceived. Half or more of the relative angle might be assigned to the centre as an absolute inclination. In the cancellation task, subjects adjusted the relative inclination by changing the disparity in the centre stimulus. In order to make the centre stimulus appear frontal, the perspective-dependent subjects should introduce a larger disparity in the centre stimulus than the disparity-dependent subjects. This is why a very large disparity was required for the perspective-dependent subjects to cancel the illusory depth in the disparity-only condition of experiment 2.

Landy, Maloney, Johnson, and Young (1995) proposed a weak fusion model of the integration of different depth cues such as binocular disparity, motion parallax, texture, and shading. They assumed that each depth cue is processed separately in an independent module to produce a depth map. Information from the different depth maps is combined linearly after a process they termed promotion. In promotion, depth information from different cues is transformed into a common unit to enable the linear summation. Different cues interact solely for the purpose of cue promotion. How does this model explain depth contrast and interaction between binocular disparity and perspective? Consider the disparity-only condition in experiment 1. The output from a perspective estimator will be 0 for both centre and surround because perspective specifies zero inclination in both. The output of a veridical stereo estimator will be 1 for the inducer and 0 for the test stimulus. Obviously, linear summation can not produce induced depth. However, it is possible that induced depth is produced within the disparity processing module, given that the output from the stereo estimator can be, say, 0.5 for the inducer and -0.5 for the test stimulus. Combining the output from the perspective estimator will reduce the perceived depth of both the inducer and the test stimulus if a heavy weight is given to perspective. This model fits perceived inclination in the disparity-only condition with the solid-square pattern in the present experiment because the perspective-dependent subjects perceived less inclination for both inducing and induced inclination. However, this model has a problem in explaining the effect of the stimulus patterns for HJ and XF. As shown in Fig. 7, induced depth in the solid-square test stimulus was larger than that in the random-dot test stimulus while the solid-square inducer appeared less inclined than the random-dot inducer. As the weak fusion model assumes linear summation among different modules, giving a heavy weight to zero-perspective will reduce the depth of both the test and inducing stimuli and changing the weight can not transform both in the same direction so that the relative depth is preserved. Thus, our results suggest that the cue combination theory provides a valid framework to explain depth contrast. The weak fusion model fits the present results only in part. Linear summation among different depth modules does not explain the results completely.

The results show that disparity–perspective cue conflict is an important factor affecting depth contrast. However, in the concordance conditions of experiments 1 and 2, a significant contrast effect occurred even when the disparity–perspective cue conflict was removed. This indicates that disparity–perspective cue conflict is not the only mechanism responsible for depth contrast. van Ee et al. (1999) measured depth contrast with real surfaces. Their observers perceived more veridical inclinations when the stimuli were real textured surfaces, in which there was no cue conflict. All depth cues specified consistent inclinations. In the concordant depth-cue conditions of the present study, disparity and perspective specified concordant inclinations, however, other depth cues such as accommodation and a depth from motion-parallax caused by the observer's small head motion, specified zero inclination. These cue-conflicts may have contributed to the residual depth contrast.

Recently, van Ee et al. (1999) examined the role of disparity–perspective cue conflict in depth contrast with different stimulus patterns. They also found large depth contrast when the inducing surface had non-zero disparity and zero perspective, and that contrast was much reduced when the inducer had concordant disparity and perspective. Their results were consistent with ours except in one condition. They found reversed depth contrast in perspective-only conditions. The central test stimulus appeared slanted in the same direction as the surround with nonzero perspective. We suggest that this inconsistency is also due to the difference between the stimulus patterns. In the experiment of van Ee et al., the central test stimulus was a random-dot pattern and the inducing surround was a cross-hatched pattern. When only perspective was introduced into the surround, a cue conflict occurred because disparity specified that both surfaces were frontal. In their experiment, the inducer appeared slanted presumably because the regular crosshatched pattern provided strong depth information. The centre appeared slanted in the same direction as the surround presumably because the random-dot texture provided only weak depth information and relative slant specified by disparity was dominant.

Kumar and Glaser (1992) also reported that the shape of the inducing surround affected depth contrast. However, in contradiction to the present results, depth contrast was minimised when the surround had inconsistent perspective and binocular disparity. We did not test a condition where the disparity and perspective in the inducer specified opposite inclination. However, the theory proposed in the present paper predicts that very large depth contrast would be observed in the inconsistent depth cue condition, because we hypothesise that absolute inclination is determined by perspective and that relative inclination is determined by disparity. We can not provide a clear explanation for the discrepancy. However, their experimental conditions, including stimulus size, duration, and viewing distance were substantially different from ours. Especially, the magnitude of the disparity and perspective they used in the experiment was very large. We suggest that our theory may not hold in highly artificial and extreme conditions, such as an inducing surround having disparity specifying 54° of slant and perspective specifying reversed slant.

5. Conclusions

We have demonstrated that disparity–perspective cue conflict is an important factor affecting depth contrast. We modified the normalization theory of depth contrast by taking account of depth-cue conflict as a reason for depth underestimation. The modified theory states the following: (1) The inclination of a surface is underestimated when depth cues other than disparity, such as linear perspective, specify zero inclination. (2) If a frontal surface is seen at the same time as a surface with inclination defined by disparity, relative inclination between the two surfaces tends to be preserved because the second-order disparity gradient provides strong information about relative depth. (3) This causes the zero-disparity surface to appear inclined in the opposite direction to the surface with disparity. (4) The magnitude of underestimation and preservation of relative inclination depends on the observers and the stimulus. (5) For a subject who uses disparity exclusively, underestimation of inclination and depth contrast do not occur. (6) When the two surfaces provide strong perspective information specifying zero inclination, the effects of relative inclination specified by disparity are reduced. For instance, the linear perspective produced by the sides of the square is stronger then the texture-gradient perspective in the random-dot disc. For this reason, both the absolute and relative disparity-induced inclinations of a solid square are underestimated more than for a textured disc. This extended theory explains the results of the present and previous studies on depth contrast that showed individual differences and dependency on the stimulus patterns.

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